THERMO-PLASTIC FINITE ELEMENT ANALYSIS FOR METAL HONEYCOMB STRUCTURE

by

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This paper deals with thermal-plastic analysis for the metal honeycomb structure. The heat transfer equation and thermal elastoplastic constitutive equation of a multilayer panel are established and studied numerically using ANSYS software. The paper elucidates that only the outer skin produces easily plastic deformation, and the outer skin still exists some residual stress and residual deformation after cooling. The dynamic evolution of plastic deformation and material performance degradation under high energy thermal load are revealed.

Key words: *honeycomb, high-temperature load, finite element analysis, plastic deformation, non-linear thermo-mechanical coupling*

Introduction

A multi-layer metal honeycomb plate is an advanced composite material for its light mass, high energy storage, and designable performance. In the normal working state, the metal honeycomb structure is subject to small deformation and stress within the elastic range. However, larger deformation will take place for a large heat load due to high temperature. Under the conditions of constraints, temperature difference and unmatched thermal expansion coefficient, larger stress is certainly caused, thus plastic deformation is probably brought.

A lot of researches had been made on metal honeycomb structure, but researches on its thermoplasticity is rare and preliminary, among which thermo-elastic analysis [1], impact damage [2, 3] and elastoplastic analysis [4-7] of metal honeycomb structure have been studied extensively, and mathematical models for thermal systems are also available in open literature [8, 9].

Problem formulation

Figure 1 is a plate with considered composite material structure to withstand heat shock. In order to ensure that the system can work normally, the structure is equipped with a thermal control facility D_1 to control and absorb heat produced by the electronic device D_2. In addition, the structure may encounter high-energy thermal load within a short period. In fig. 1, heat flows vertically to the outside surface with heat flux q. The heating source is moved out after 20 s and the heating period is 20 s. Metal honeycomb structure consists of inner skin, outer skin and honeycomb core. They are jointed *via* adhesives, and are fixed by screws. Because honeycomb structure easily produces debonding after the adhesives are heated, it will

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have the great influence on performances of honeycomb structure. Here we consider the adhesives as a separate layer. In order to overcome the grid-divided difficulty for a large number of honeycombs, we consider it as an equivalent plate as illustrated in fig. 2. The geometric dimensions of the structure are: length 2000 mm, width 1000 mm, total thickness 26.5 mm, where thickness of the skin, adhesive layer, and honeycomb core are 0.5 mm, 0.05 mm, and 25.4 mm, respectively.

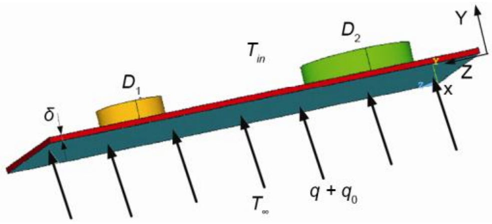


Figure 1. Load of metal honeycomb structure

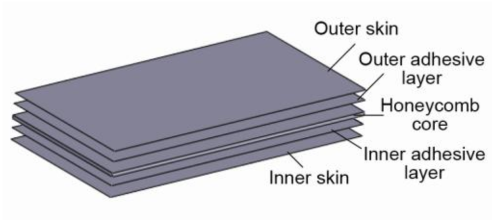


Figure 2. Composition of metal honeycomb

Mathematical model and solving methods

Heat transfer equation

In the loading process, there are high energy heat flux and natural environment heat flux vertical to the outer surface of the structure, their density are q and q_0, respectively, heating power produced by electronic components is ϕ, both outer surface and inner surface carry out convection heat exchange to the environmental temperature (20 °C). The transient heat transfer conduction equation [9] can be written:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \dot{\phi} \tag{1}$$

where ρ is the density, c – the capacity, k – the heat conductivity coefficient, and T – the temperature of the structure. Heat convection between the inner surface and internal environment is:

$$-k\left(\frac{\partial T}{\partial y}\right) = h_\delta (T_{s,\delta} - T_{in}) \tag{2}$$

where h_δ is the heat transfer coefficient of $y = \delta$ surface, $T_{s,\delta}$ – the temperature of $y = \delta$ surface, T_{in} – the internal environment temperature, and T_{in} = 20 °C. The heat convection equation between the outer surface and the external environment is:

$$-k\left(\frac{\partial T}{\partial y}\right) = q + q_0 - h_0 (T_{s,0} - T_\infty) \tag{3}$$

where h_0 is the heat transfer coefficient of $y = 0$ surface, $T_{s,0}$ – the temperature of $y = 0$ surface, T_∞ – the environment temperature, and T_∞ = 20 °C. The governing equation after thermal load ending is:

$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \dot{\phi} = 0 \tag{4}$$

Thermal elastoplastic equation

Because adhesive is a kind of flexible materials in a certain temperature range, the inner skin, honeycomb core and the outer skin are only considered for thermo-plasticity.

The inner skin

The temperature of the inner skin is lower, and its deformation is elastic in the loading and unloading process. In the elastic region, incremental stress-strain relation is:

$$\Delta\{\sigma\} = [D](\Delta\{\varepsilon\} - \Delta\{\tilde{\varepsilon}\}_T) \tag{5}$$

where $[D]$ is elastic matrix, $\Delta\{\tilde{\varepsilon}\}_T = [\{\alpha\} + \mathrm{d}[D]^{-1}/\mathrm{d}T\{\sigma\}]^T \Delta T,$ and α – the linear expansion coefficient.

Because material parameters vary with thermal load, the incremental tangent stiffness method is adopted to solve the equilibrium equations. The equivalent nodal load $\bar{R}_T$ is:

$$\{\bar{R}_T(\Delta\{\sigma\})\} = \int [B]^T [D]\Delta\{\tilde{\varepsilon}\}_T \,\mathrm{d}V \tag{6}$$

The overall stiffness equation is:

$$[K]\Delta\{\delta\} = \Delta\{R\} + \{\bar{R}_T(\Delta\{\sigma\})\} \tag{7}$$

where $[K]$ is the overall stiffness matrix.

An iteration method is constructed as:

$$[K]_n \Delta\{\delta\}_n^j = \Delta\{R\}_n + \{\bar{R}_T(\Delta\{\sigma\})\}_n^{j-1},\ \mathrm{j} = 0, 1, 2, \ldots,$$

$$\{\delta\}_n = \{\delta\}_{n-1} + \Delta\{\delta\}_n, \quad \{\varepsilon\}_n = \{\varepsilon\}_{n-1} + \Delta\{\varepsilon\}_n, \quad \{\sigma\}_n = \{\sigma\}_{n-1} + \Delta\{\sigma\}_n. \tag{8}$$

Honeycomb core

For heat resistant properties of the adhesive and thicker honeycomb core, its deformation is also elastic in the loading and unloading process. The performance matrix of the equivalent materials is orthotropic and anisotropic. The solving method of the strain field is same as one of the inner skin.

The outer skin

Since the restricted outer skin is irradiated directly by high-intensity heat flux, its stress is higher, which can result in the plastic deformation. Suppose each load step is smaller, in the plastic region, the incremental stress-strain relation is:

$$\Delta\{\sigma\} = [D]_{ep}(\Delta\{\varepsilon\} - \Delta\{\tilde{\varepsilon}\}_T) + \Delta\{\tilde{\sigma}\}_T \tag{9}$$

where $[D]_{ep}$ is the elastoplastic matrix at k^{th} iteration, and $\Delta\{\tilde{\sigma}\}_T$ – the incremental plastic-strengthened temperature stress.

In the transitive region, incremental stress-strain relation is:

$$\Delta\{\sigma\} = [\bar{D}]_{ep}(\Delta\{\varepsilon\} - \Delta\{\tilde{\varepsilon}\}_T) + \Delta\{\tilde{\sigma}\}_T \tag{10}$$

where $[\bar{D}]_{ep}$ is weighted average elastoplastic matrix, $[\bar{D}]_{ep} = m[D] + (1-m)[D]_{ep}$, $[D]$ – the elastic matrix, m – the ratio of the elastic strain to the strain difference in the transitive region.

Using $[D]_{ep}$ and $[\bar{D}]_{ep}$ to replace $[D]$ in eq. (5) and compute the equivalent load, we can conduct the stress analysis in same method as one in the elastic region.

Numerical calculation and analysis for results

In case of the load and performance parameters (tabs. 1 and 2) to be determined, a finite element model for the studied structure is built, the transient computations are carried out during the loading and unloading processes. Among these, the temperature in the loading process is load for structure calculation, the temperature at the end of loading process is the initial condition for thermal calculation in the unloading process.

Table 1. Main load parameters of metallic honeycomb structure

Main load parameters	Symbol	Value
External heat flow density	q	11 W/cm^2
Natural environment heat flow density	q_0	0.1388 W/cm^2
Heating power of thermal control equipment	Φ_1	100 W
Heating power of electronic device	Φ_2	80 W
Hemisphere emission rate	ε	0.8
Solar absorption	α	0.8

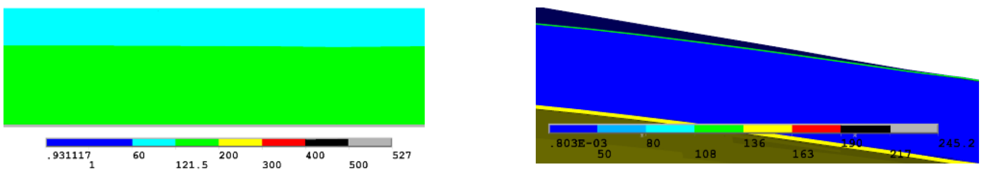
The results and analysis are shown in tabs. 1 and 2.

Table 2. Linear expansion coefficient, elastic and shear modulus of honeycomb core and yield strength of aluminum alloy

Temperature [°C]	Linear expansion coefficient [10^{-6} °C]	Yield strength [MPa]	Material parameters	Elastic modulus [Pa]	Shear modulus [Pa]
20	24.2	275	E_x/G_{xy}	1.6456e5	4.1149e4
100	26.6	250			
200	26.8	227	E_y/G_{yz}	1.6464e5	1.5588e8
300	27.6	210	E_z/G_{xz}	8.2307e8	2.3383e8
400	28.9	175			
500	30.2	125			

Transient analyses in the loading process

Considering the yield strength is closely related to temperature, so the determination of plastic deformation must combine with the temperature field. Figure 3 illustrates temperature field and stress field distribution of honeycomb structure section while loaded 20 s.



(a) Temperature field distribution [°C] (b) Stress field distribution [MPa]

Figure 3. Temperature field and stress field distribution of honeycomb structure section loaded 20 s
(for color image see journal web site)

As seen in fig. 3, due to the function of the adhesive, honeycomb core has good heat insulation performance, temperature and stress of the inner skin is lower, plastic deformation does not arise. Because of the large thickness and the lower temperature of median honeycomb core, its resistance to bending is higher, thus its stress is also lower, so the plastic deformation does not also appear. However, the outer skin is irradiated directly by high-intensity heat flux, and meantime it is very thin and is fixed around, so a higher stress is bound to be produced, and plastic deformation is easily brought about. The details are shown in fig. 4.

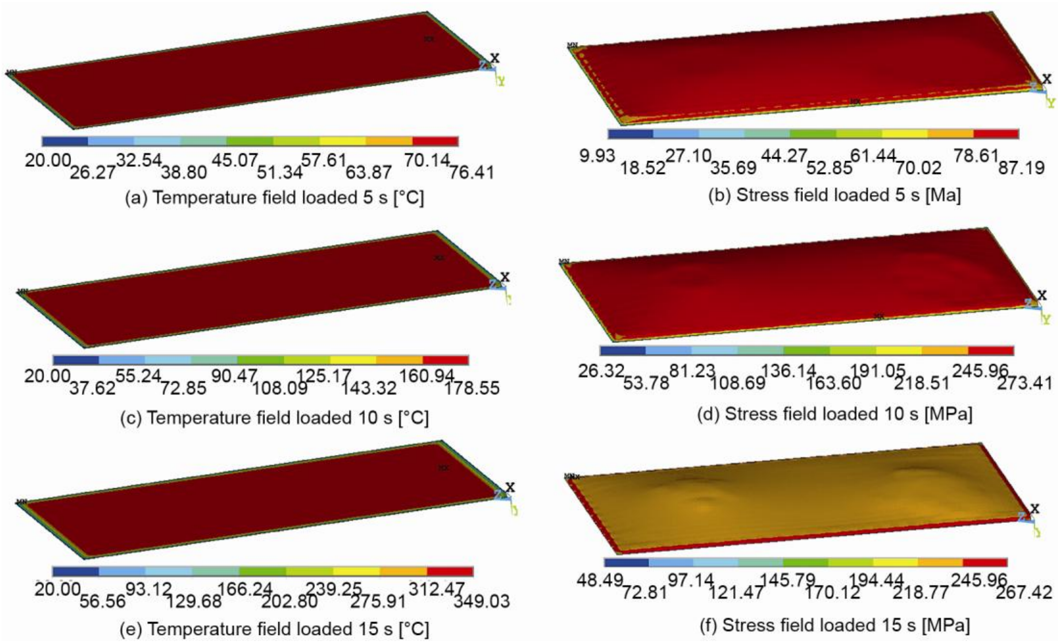


Figure 4. Fields of temperature and stress of the outer skin at different loaded time
(for color image see journal web site)

As shown in fig. 4, while loaded to 5 s, the highest temperature is less than 80 °C, yield strength is above 200 MPa, but the stress is below 90 MPa, and so plastic deformation does not appear. While loaded to 10 s, temperature is between 160 °C and 180 °C in most of regions, yield strength is below 249 MPa, but stress in overall plate is higher than 245 MPa, it predicates that plastic deformation has already existed. While loaded to 15 s, temperature in most regions is from 300 °C to 350 °C, yield strength is less than 210 MPa, whereas the stress exceeds primarily 218 MPa, it clearly states that the whole outer skin is almost in plastic state at this time, and deformation all around is more serious than the middle area. Compared to 10 s, temperature rises further, as a result of the enlarged deformation, the stress in mid region decreases oppositely, but the plastic area and level become more severe.

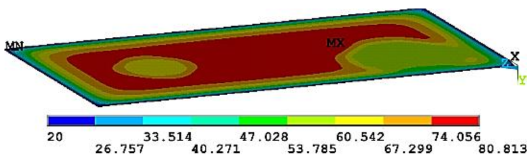


Figure 5. Temperature field while releasing heat-load [°C]
(for color image see journal web site)

Steady-state analysis in the unloading process

Figure 5 denotes temperature field distribution of the outer skin when the heat-load is released 6000 s. It can be seen that temperature is higher in the middle region apart from the corresponding equipment locations, the highest is approximately 81 °C, the temperature is lower nearby the boundary. Figure 6 shows temperature curves of the outer skin *vs.* time unloaded. As shown in fig. 6, variation tendency of temperature in different locations *vs.* time is

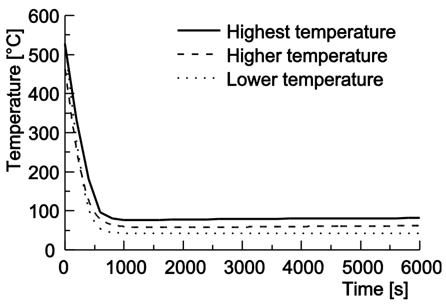


Figure 6. Temperature of the outer skin

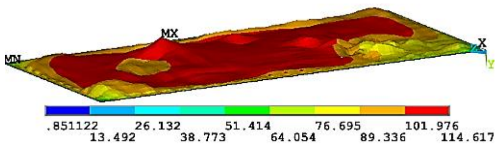
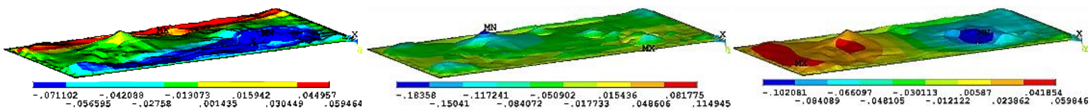


Figure 7. Residual stress distribution of the outer skin unloaded 6000 s [MPa]
(for color image see journal web site)

demonstrated distinctly, the temperature declines rapidly unloaded, then falling speed slows down gradually, holds a constant until 6000 s, and it reveals that a steady-state has reached at the moment.

Figure 7 shows residual stress distribution of the outer skin while unloaded 6000 s. In fig. 7, stress is higher in the middle region except the corresponding equipment locations, 100 MPa or so, stress is lower border round the skin, the distribution laws are accordant with temperature filed. But higher stress concentration occurs in the vicinity of a device mainly because of constraints, device and temperature difference, the highest stress is about 115 MPa.

Figure 8 illustrates residual deformation distribution of the outer skin while unloaded 6000 s in different directions. It is obviously seen that there are all residual deformation in three directions, but residual deformation is largest in the heat-loading direction, and maximum is around 0.18 mm.



(a) X-direction (b) Y-direction (c) Z-direction

Figure 8. Residual deformation distribution of the outer skin unloaded 6000 s in different directions [mm]
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Figures 9 and 10 indicate, respectively, stress and deformation in Y-direction curves of the outer skin unloaded.

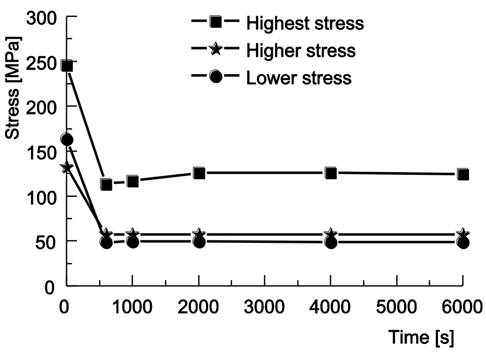

Figure 9. Stress curves of the outer skin unloaded

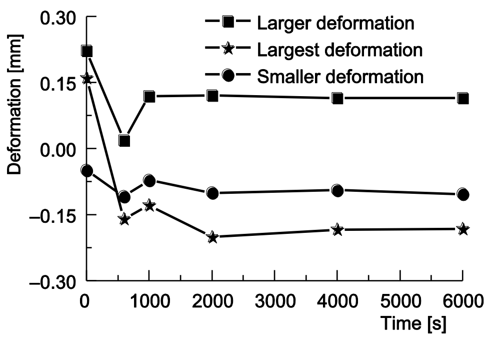

Figure 10. Deformation curves of the outer skin unloaded in heat-loading direction Y

It is seen that both stress and deformation drop quickly first, variation speed slows down afterwards, gradually become stabilized. However there are still some residual stress and deformation finally. It indicates that plastic deformation has been existed in the structure. In addition, plastic deformation becomes severe in some regions in the cooling process due to the influence of constraints, devices, and internal interaction.

Conclusions

Based on the established model and the computation results using finite element method for transient thermal loaded and unloaded processes, the following conclusions can be drawn.

- The outer skin easily yields plastic deformation when it is subjected to a high-energy thermal load for a short time.
- The overall outer skin produces plastic deformation except for the case when the heating period is less than 15 s, and the region and degree of deformation will be further enlarged with the heating time.
- The residual stress of the outer skin near the middle region is higher, and the residual stress of the outer skin near the boundary and corresponding device locations is lower, meantime, the more serious stress concentration also appears. Moreover, there is a greater residual deformation in the heat-loading direction.

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